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EYE LINE-OF-SIGHT CONTROL COMPARED TO MANUAL SELECTION OF DISCRETE SWITCHES (U)

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-3.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Laboratory

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13. ABSTRACT *(Maximum 200 words)*

Eye-controlled switching has been proposed as a biocybernetic control approach which may increase system effectiveness while reducing pilot workload. In this experiment, six subjects selected discrete switches on the front panel of a cockpit simulator while manually tracking a target. In two eye-controlled methods, the subjects directed their gaze at the switch indicated by an auditory cue and then made a consent input (either a manual response or a verbal response). In a conventional manual condition, subjects selected the switches with their left hand. The analysis of mean switching time suggests that eye control is a feasible alternative when hands-off control is desired. Tracking performance was found to differ significantly among switching conditions, indicating the importance of quantifying the efficiency of candidate control methods in visual workload environments analogous to that of the application environment.

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PREFACE

This technical report is the result of research performed at the Visual Display Systems Branch (HEA) of Detachment 1, Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio. Dr Thomas Furness was chief of the branch and Ms Gloria Calhoun was responsible for the research. Mr Jim Shaw and Ms Jenny Huang of Systems Research Laboratory, Inc. (SRL) provided software support, Dr Christopher Arbak and Mr William Janson (SRL) provided human factors support, and Mr Charles Goodyear and Ms Rebecca Donovon (SRL) provided support in the statistical data analyses. This effort was accomplished under Work Unit 71842602 between January - September 1985. The SRL portion of this effort was performed in support of the USAF AAMRL under Contract Number F33615-82-C-0511. This effort was funded, in part, by Armstrong Aerospace Medical Research Laboratory Laboratory Director Funds.

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INTRODUCTION

A major challenge for the design of future cockpit control systems is to increase system effectiveness while reducing pilot load. It has been suggested that biocybernetic control approaches could be used to enhance pilot performance in future cockpit configurations (Nicholson, 1966; Merchant, 1980; Calhoun, Arbak, and Boff, 1984). More specifically, much attention and speculation has focused on the use and potential advantage of eye-controlled switching. Furness (1978) figuratively illustrates how a pilot could "shift his line-of-sight to labeled control surfaces in order to initiate various functions in the cockpit" (e.g., select weapons, display modes, etc.). In this example, eye control eliminates the need for selective manual responses by substituting the movements of the eyes which are inherent to the visual task. The speed and accuracy of the eye and oculomotor system (Yarbus, 1967) appear to substantiate claims of enhanced efficiency for eye control. However, this advantage is not obvious under task-loaded conditions. If eye-controlled switching is to be seriously considered for application in future biocybernetic cockpits, then it should be compared to conventional approaches in visual workload environments analogous to that of the single seat cockpit.

Although some literature exists on the use of eye movement data to improve cockpit panel layout and instrument design (Barnes, 1970; Dick, 1980), little data is available on the effectiveness of using eye line-of-sight as a control interface. Earlier systems were bulky and required that the head be fixed (Young and Sheena, 1975). Such obstacles are substantially reduced by the Honeywell Helmet-Mounted Oculometer System built for the Air Force (Aeronautical Systems Division, Project 2360; schematic shown in Figure 1). The modified flight helmet, with the liner removed and the head and eye movement sensors mounted on it, weighs only 0.198 kg more than the standard Air Force helmet. The Honeywell system, as well as others under development, facilitate research examining eye control of aircraft system functions by enabling the operator to freely move the head and eyes and purposely shift the head and eye line-of-sight towards switches, displayed symbols, or out-the-window targets. These candidate applications are illustrated in Figure 2.

PURPOSE

The present experiment examined manual switching compared to two eye line-of-sight switching methods in a dual task paradigm. The subjects' task was to select discrete switches on the front panel of a simulator while manually tracking a target. In the two eye-controlled methods, the subjects directed their gaze at the switch indicated by an auditory cue and then made a consent input (either a manual response or a verbal response). In a conventional manual method, subjects selected the switches with their left hand. Switching time and accuracy were recorded as well as manual tracking performance.

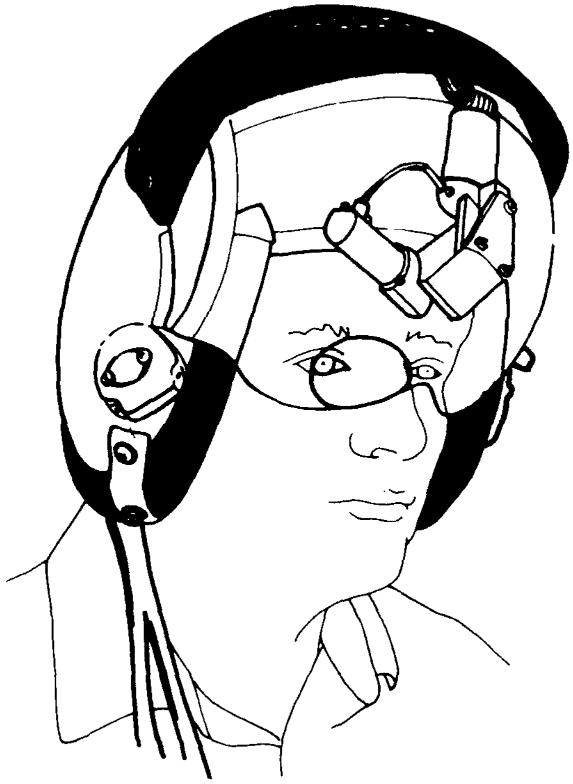


Figure 1. Schematic of the Honeywell Helmet-Mounted Oculometer.

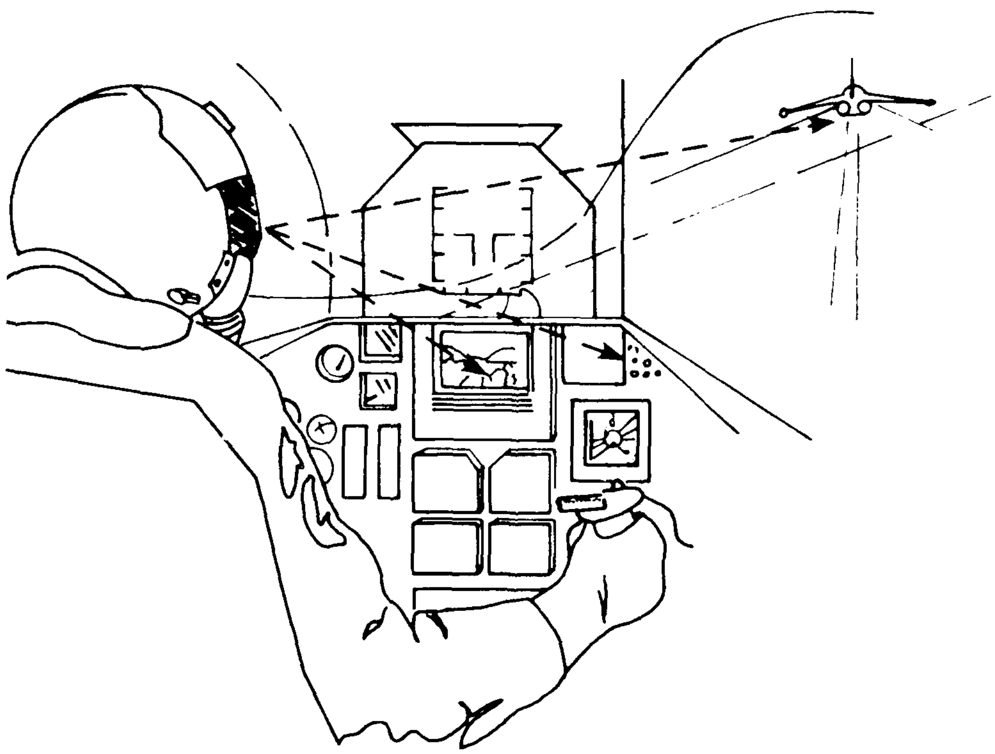


Figure 2. Illustration of Eye Control Applications in Crew Station Design.

METHOD

APPARATUS

The research was conducted in the Helmet-Mounted Oculometer Facility (HMOF) residing at the Armstrong Laboratory, Wright-Patterson Air Force Base. The overall configuration of the facility is shown in Figure 3. The key components of the facility which pertain to this study are described below.

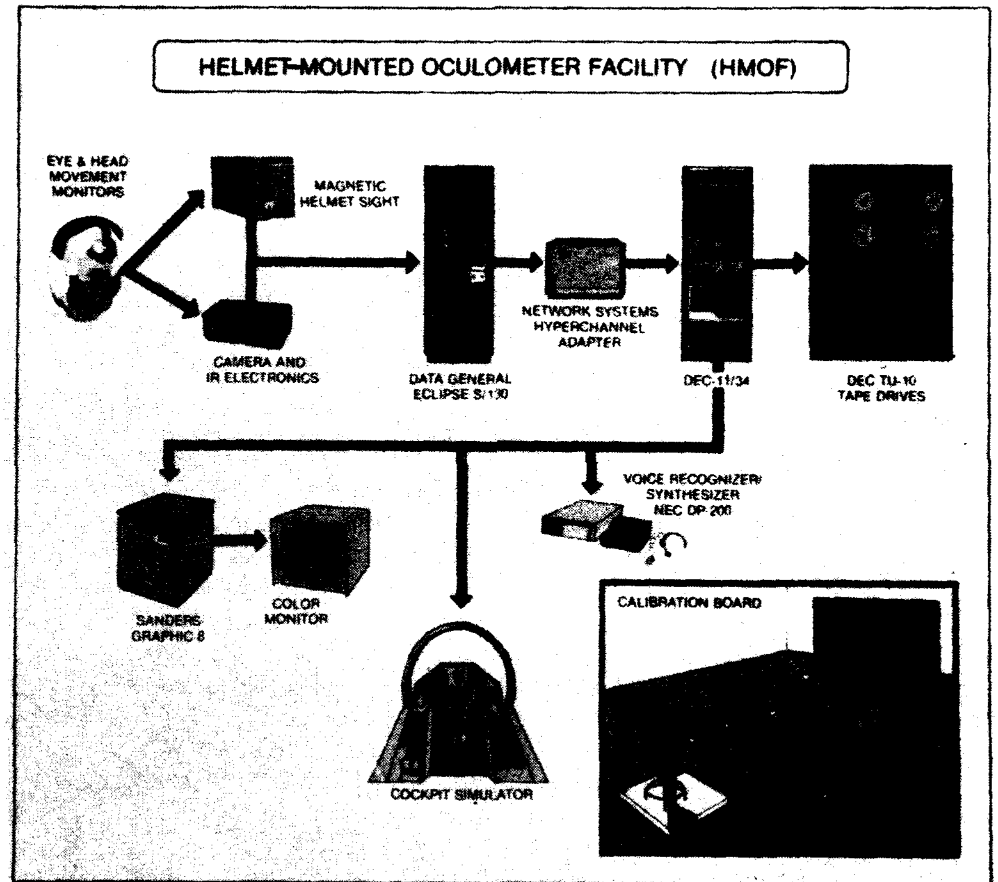


Figure 3. Overall Configuration of the Facility.

Eye Movement Recording System. The movement of the eye with respect to the head was measured with an infrared corneal reflection system (modified Honeywell Helmet-Mounted Oculometer; Figure 1). The subject's eye was illuminated by a halogen lamp filtered to pass near-infrared light. This light was collimated and reflected from a small coating on a parabolic helmet visor into the subject's right eye. Some light was reflected from the cornea and a portion of the light that entered the pupil was reflected by the retina, passed out of the eye

through the pupil, and was scanned by a miniature charge-coupled device (CCD) video camera. The video signals from the camera contained bright spots, a bright disk, and spurious background reflections. The bright spots resulted from tears and reflections of the light source from the surface of the cornea and the bright disk was the reflected energy from the retina after it had passed through the pupil.

As the cornea and the rest of the eye have different radii of curvature, eye rotation about the visual field will result in differential movements of the corneal reflection with respect to the pupil. Thus, true eye azimuth and elevation angles with respect to the helmet was determined by complex signal processing which sorted pupil and corneal reflections, determined the relative positions of the center of the pupil and the center of the corneal reflection, rejected tears, and accounted for the nonlinearity of raw subject data.

Head Movement Recording System. A Honeywell magnetic Helmet Mounted Sight (HMS) provided accurate helmet position and attitude determination in six degrees-of-freedom with respect to a fixed coordinate system. The HMS utilized a transmitter mounted behind and above the subjects' helmet to create a magnetic field around the simulator and a helmet-mounted receiver which responded to movement through this field by varying the output voltages. A Honeywell HDP-5301 computer integral to the HMS System computed helmet position and rotation based on these voltages.

Supporting Computer/Software System. Eye angle data and helmet rotation and position data were combined by software residing in a Data General Eclipse S/130 computer to determine eye line-of-sight with respect to a fixed coordinate system. These data were sampled and line-of-sight computed at a 60 Hz rate. Root-mean-square (RMS) error was 0.45 degrees or less at most eye positions. The oculometer system was connected to a PDP-11/34 mini-computer via a Network Systems Hyperchannel Adapter. The PDP-11/34 was used to control presentation of switching cues and tracking symbology, as well as to record eye/head parameters and performance data. All data were analyzed on an IBM Systems 370 computer following the conduct of a format conversion program.

Simulator. A single-seat simulator of A-7 geometry containing two monitors and a switch panel was utilized (Figure 4). The upper centrally-located monitor was approximately 66 cm from the subjects' eye, subtending a visual angle of 8.5 x 10.7 degrees. Seven dedicated switches were mounted on a panel (see Figure 5) positioned on the upper portion of the front panel. These momentary switches measured 14 x 20 mm. The middle switch was at an approximately 67.3 cm viewing distance, subtending a visual angle of 1.2 x 1.7 degrees. The switches were labeled with black numerals 1 through 7. Switch 7, as well as the color monitor located below the switch panel, were not used during the experiment.

A pressure-sensitive 12.5 x 12.5 mm switch plate was mounted on the

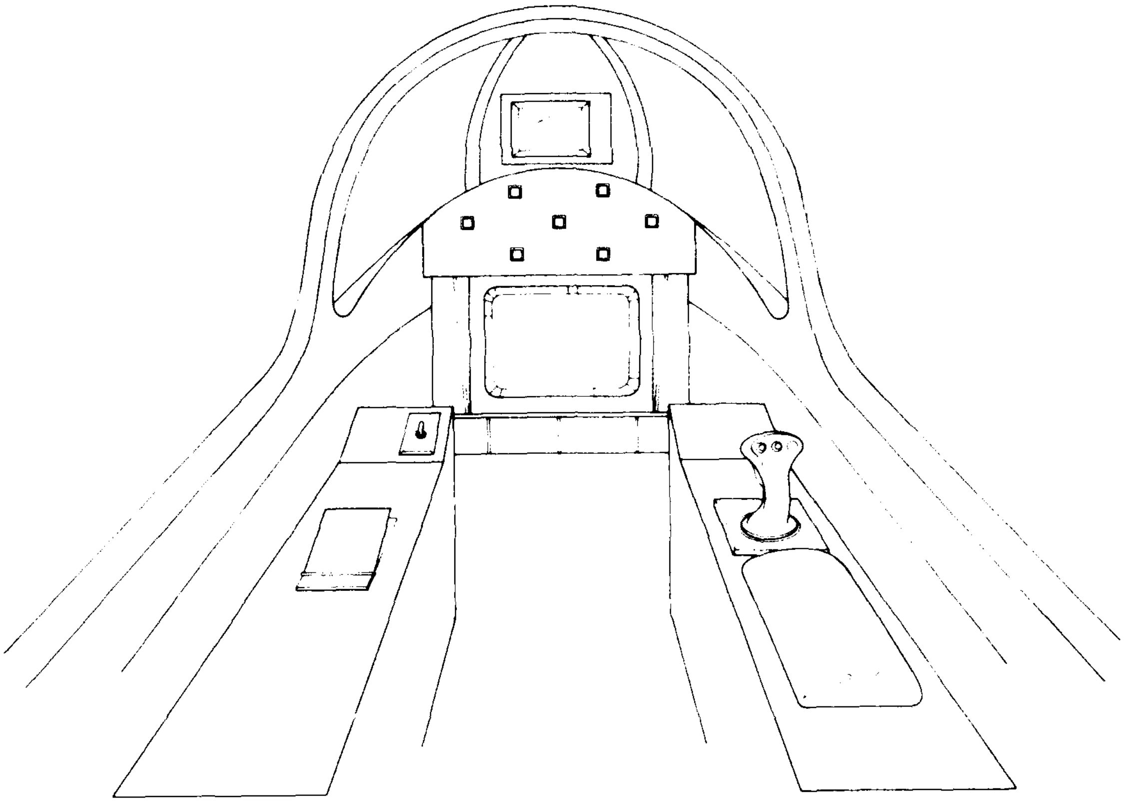


Figure 4. Schematic Illustration of the Simulator.

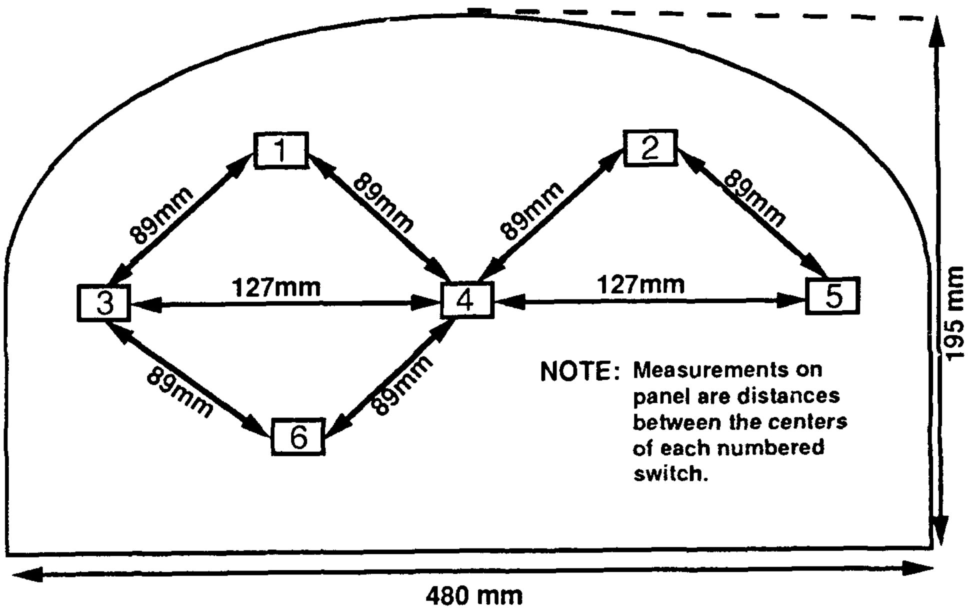


Figure 5. Schematic Illustration of the Switch Panel.

left console. The right console force stick was fitted with 4 switches, 2 of which were thumb-actuated push-buttons. In addition, an arm rest was located behind the stick. Both an intercom and voice synthesis system were connected to the helmet, enabling the subject to communicate with the experimenter and hear switch cues. During testing, the simulator was surrounded by a black curtain extending from the floor to the ceiling and the room lights were dimmed. The average luminance of the switches, when lighted, and the symbology on the upper monitor was 2.92 and 0.17 cd/m^2, respectively.

Experimenter's Station. The station was equipped with a monitor and status lights which provided the experimenters with the capability of monitoring both the tracking display and the switches selected. An additional monitor displayed the image of the eye as viewed by the CCD camera.

SUBJECTS

Subjects were 6 paid members of a contractor-maintained pool. The mean age of the 3 male and 3 female subjects was 24.17 years. The subjects' corrected vision was 20/20, as determined by an optometrist's examination; one of the subjects wore soft contact lenses and his data was indistinguishable from the other subjects' data. While five of the six subjects were right-handed, handedness was not used as a selection criterion since the subject's tracking performance was required to reach asymptote and handedness has been found to have little effect on tracking performance (Wilson, 1972).

Each subject was administered a standard information and consent form prior to the experiment (see Appendix A). All procedures and requirements of the Air Force pertaining to the subjects' rights, protection, and safety were satisfied.

EXPERIMENTAL DESIGN

The design employed was a 3 x 2 within-subject factorial (repeated measures) design. The independent variables were switching method (manual, eye-control with manual consent, eye-control with voice consent) and tracking condition (tracking versus no tracking). The first independent variable was blocked, with subjects receiving trials with each tracking condition within switch method blocks. For each switching method, subjects completed two sessions without tracking -- one session before and one session after the sessions with tracking. The order in which the switching methods were presented was determined by the use of a balanced Latin Square such that, across subjects, each method was preceded equally often by each of the other methods. The order in which each of the six switches was selected was randomized with the constraint that each switch was cued an equal number of times during each run.

SUBJECTS' TASKS

For the majority of the sessions, each subject completed two

concurrent tasks: a manual tracking task presented on the centrally-located monitor and a task involving the selection of switches located just below this monitor. A pay-off matrix was used to help equate the allocation of attention between the tracking and switching tasks. If mean performance on either task deteriorated from the previous day's performance, no bonus was awarded. If performance improved by more than 1 standard deviation (sd) on both tasks, then the maximum monetary bonus was awarded. Improvements of less than 1 sd on one or both tasks were awarded a lesser amount. (See Appendix A for Subject Instructions. A total of $23.25 was awarded in bonuses.)

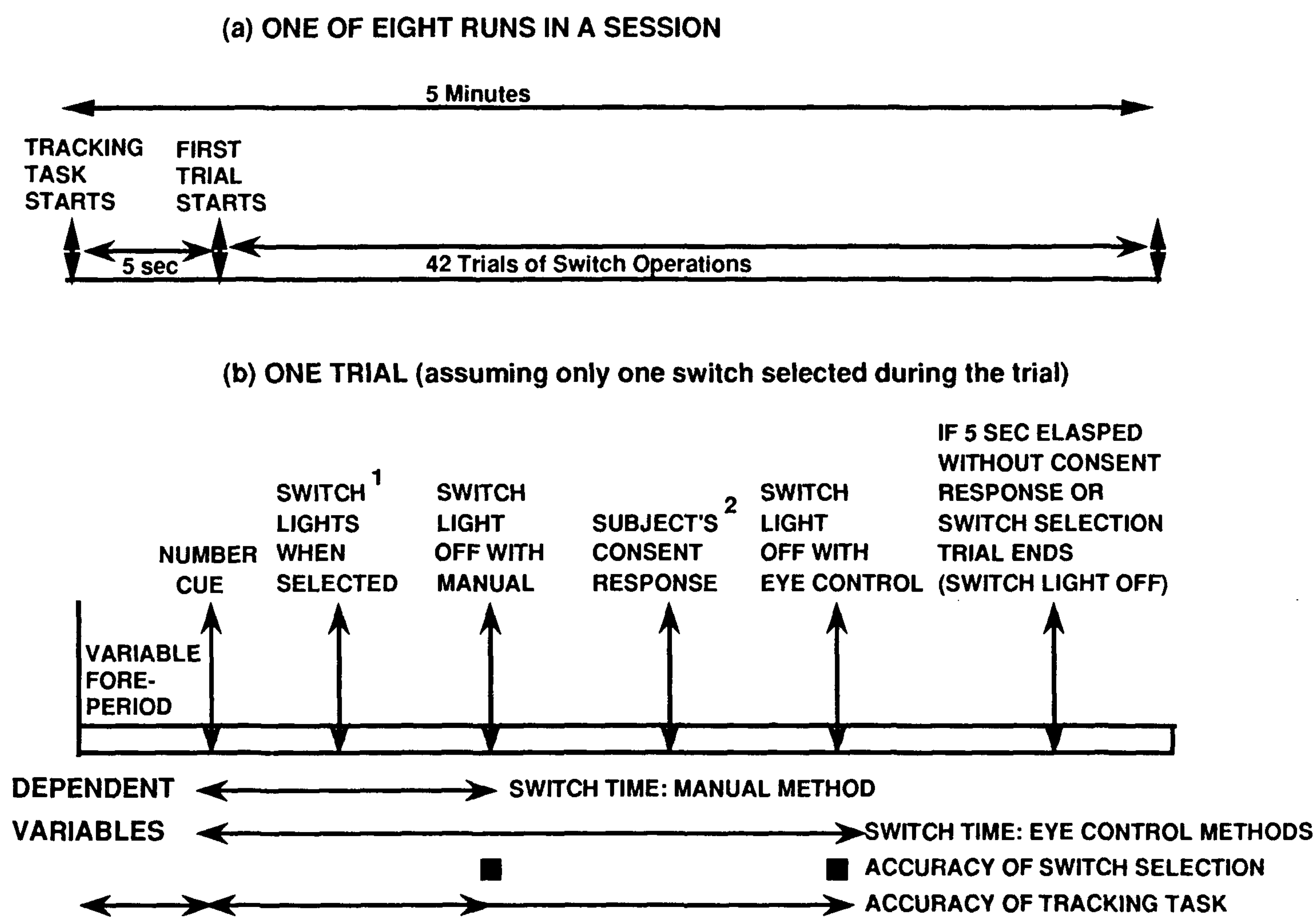
Tracking Task. The subjects were required to complete a manual pursuit control tracking task on the centrally-located monitor. The tracking symbology consisted of a dot as a command input and a cross hair as the system output. The subjects' task was to keep the dot on top of the cross hair by exerting pressure on the force stick which controlled the position of the dot on the monitor. Performance in terms of RMS error on the tracking task was based on the distance (in inches) between the dot and the cross hair.

Summed sine waves were used as the input forcing function. There were eight sinusoidal components which moved in both the vertical and horizontal planes so that the input appeared to the subject as a random process. The bandwidth of the sinusoidal components was 0.3 Hz and the component sine waves were identical in amplitude. A number of forcing functions differing in the phase relationships of the components were generated and randomly assigned to the runs.

Switching Task. In each five-minute run, an auditory cue ("one", "two",..."six") corresponding to the switches numbered 1 through 6 was presented forty-two times while the subject was completing the tracking task. The switch cues were presented at a random interval of 5 to 9 seconds (mean of 7 seconds). (See Figure 6 a and b, for an illustration of the events in one run and one trial, respectively.)

In the conventional manual switching method, subjects selected the cued switch on the front panel by pressing the switch using their left hand. The switch was illuminated during the switch closure. Once a switch was selected, the switch light was extinguished and the switch panel became inactive until the next auditory cue was presented. Between switch selections, subjects were required to keep their left hand on the left console switch plate and the position of this switch was recorded continuously throughout the run. Reaction time (time from the cue until the front panel switch was selected) was recorded as well as the accuracy of the switch selection.

In the two eye-control methods, subjects directed their gaze at the cued switch. When the system detected that eye line-of-sight was directed within 2.54 cm of the center of a switch for two of three consecutive samples (at least 33.4 msec), that switch was illuminated, as feedback to the subject. The switch remained illuminated until: 1) another switch was selected, 2) a five-second "time-out" interval had expired, or 3) a consent response was made. In one eye-control method,



1 Either manually hit or eye line-of-sight within 2.54 cm of switch center for 2 of 3 samples

2 Either consent button pressed or verbal response recognized

Figure 6. Illustration of Events in each Run and Trial.

subjects manually closed a push-button located on the force stick for the consent response. In the second eye-control method, the consent consisted of uttering the word "go" into the helmet-mounted microphone. The subject then heard through the intercom either the word "go" or a beep for feedback as to whether the speech system successfully recognized the utterance. When the system beeped, indicating the response was not recognizable, the subject repeated the word "go", until either the system recognized the response or the five-second "time-out" interval had expired. Reaction time was measured from the verbal cue to when the consent (manual or verbal) was completed. Each switch lit during the switching trial was also recorded so that the accuracy of the final switch selection could be determined, as well as how many, and which switches were selected prior to the consent response.

PROCEDURES

Linearization. Prior to the experimental sessions, each subject completed a linearization procedure in order to map the unique geometry of the subject's eye to known line-of-sight angles. In this procedure, each subject, while maintaining a stable helmet position and attitude, sequentially fixated 51 light-emitting diodes which were positioned at known eye rotation angles. In this manner, the pupil video and corneal signals could be correlated with the known spatial data points. The procedure lasted approximately one hour.

Set-Up. Each subject was seated in the simulator with the seat adjusted so that the center of the centrally-located monitor was at the subject's eye level (distance approximately 0.63 m). The helmet was then fitted over the subject's head and was held in place by helmet pads, a chin-strap and air bladders over the ears. The subject was also required to wear cotton gloves to help protect the reflective patch on the visor. If it was the subject's first session, a detailed explanation was given of the nature of the experiment, the subject's tasks and schedule (Appendix A; The instructions were only reviewed if this was not the subject's first session.) A calibration procedure was then completed. To complete this procedure, the subject sequentially fixated six symbols displayed on the upper monitor and each of the six switches on the switch panel. During each fixation, the computer sampled the eye position signal and stored the values for use later in translating the eye and head monitoring signals, in relation to the current helmet fit, to positions in the simulator. At least the last five minutes of the initial set-up period were conducted in the dark for eye adaptation.

Experimental Sessions. Eight 5-minute runs constituted a session. After 4 runs, subjects were given a short break in the simulator. A maximum of eight runs were conducted per day, with the subject's infrared exposure limited to 1 hour every 48 hours. Thus, testing for each subject was limited to 3 days per week and each session, including set-up, lasted approximately 1.25 hours.

Test sessions were conducted over a 16 week period of 47 testing days. For each switching method, two test days (16 runs) without

tracking were conducted: 8 runs before and 8 runs after sessions with tracking. The last four runs on each of these two single task sessions with each switching method were saved (total of 6048 trials).

At least three sessions with tracking were conducted with each switching method. Additional dual task sessions were conducted with each method, after the required three sessions were completed, until performance, in terms of mean RMS tracking error and mean switching time: 1) fluctuated less than 7% over four consecutive runs (168 switching trials) and 2) was within 10% of performance on the previous session. Data from the final four dual task runs for each of six subjects per switching method were analyzed (3024 switching trials).

DATA ANALYSES

Performance Data. The following data were analyzed as a function of switching method and cued switch:

mean switch selection time: average time to select a switch (from verbal cue until: 1) the last switch lit by eye-control prior to the consent response, or 2) switch manually selected);

mean switch activation time: average time to complete switching operation (from verbal cue until switch activation, including time to make the consent response in the two eye-control methods; note, activation and selection time are identical in the manual switching method);

number of switches selected prior to the consent response in the two eye-control methods;

tracking performance (RMS) during the switch activation time for those sessions in which the subjects also completed the manual tracking task; and

frequency of error trials for switch activations which were not completed (i.e., switch not selected or consent not made) or completed incorrectly.

Switching operations completed without errors were analyzed separately from trials in which switch activations were not completed or completed incorrectly (4.03% of the trials). For the error-free data, each of the factors was treated in an analysis of variance (ANOVA). In those cases where the ANOVA revealed significant effects, the Neuman-Keuls multiple comparison test was conducted.

Only main effects were examined in the analyses of error data, due to the small number of trials and numerous missing cells. For instance, when analyzing the switching error trials, the vast majority of errors occurred in the eye control/voice method as opposed to the eye control/manual and manual methods. For the error data, two approaches were used in the analyses: 1) analyzing the data using the method of least squares and conducting an ANOVA and 2) performing data

transformations and then analyzing these transformed values using ANOVA. The least squared means (LSMEANS) approach (with subject considered a fixed factor) resulted in comparable means for each method when cell sizes were not equal. With the data reported herein, LSMEANS was used when analyzing effects such as switch activation time and tracking performance. The data transformation approach was used to analyze frequency data, i.e., the number of switching errors or timeouts across switching methods. The transformations involved adding 0.5 to each data value and then taking the square-root as recommended by Kirk (1968). These transformed values were then analyzed using ANOVA. Non-parametric approaches to analyzing these data were not adopted due to the small number of subjects.

Subjective Data. Subjective data gathered through aebriefing questionnaires were compiled to be presented in tabular form and analyzed using Kolmogorov-Smirnov nonparametric tests of significance. The results for each item on the questionnaire are presented in Appendix 3.

RESULTS

The results of the statistical analyses conducted on the subjective and objective data are presented. (All tests conducted at alpha = 0.05.) The findings of the data analyses examining dual task sessions (i.e, subjects completing both switching operations and tracking task) are presented first, followed by the results of analyses conducted on the single task sessions involving switching operations only. Within each of these areas, analyses of the error-free trials are addressed separately from the results of analyses involving error data.

DEBRIEFING QUESTIONNAIRE DATA

The subjects' responses to the debriefing questionnaires, along with the results of the statistical analyses, are shown in Appendix B. Analysis of the subjects' rankings of the three switching methods did not show any significant differences. On three questions, the subjects failed to rank any of the switching methods significantly better in terms of a) overall usability, b) speed in completing switching operations, c) accuracy in completing switching operations, and d) interference with the concurrent tracking task.

ERROR-FREE TRIALS - DUAL TASK SESSIONS

The following results pertain to error-free switching operations in which the subjects were also completing the manual tracking task (2902 trials).

Switching Methods. The results showed that the mean switch activation time was significantly different across switching methods, $F(2,10) = 87.31$, $p = 0.0001$. Switching time was longer with the eye control/voice consent method (2.84 seconds) than with the eye control/manual consent method (1.79 seconds) or the manual method (1.72 seconds), $p < 0.05$ (Figure 7).

It is important to note, however, for the eye control/voice consent method, the time required for the voice system to recognize an utterance and transmit the results to the host computer makes up a component of the total switching time (0.92 seconds). Subtraction of the equipment-induced response lag from each eye control/voice consent switching time (corrected mean = 1.93 seconds), and examination of these data indicate that the differences in mean times for the three switching methods are not significant ($F(2,10) = 2.48$, $p = 0.134$). For the remainder of this report, results pertaining to switch activation time are from analyses which have subtracted out the voice system response lag.

The voice system delay was not a factor in the time to select switches, and analysis of these data indicated that the mean switch selection time was significantly different across switching methods, $F(2,10) = 8.16$, $p = 0.0079$, Figure 8. The results indicated that it took the subjects 0.29 seconds longer to select switches with the manual method than with the two eye-control methods ($p < 0.05$). In the two

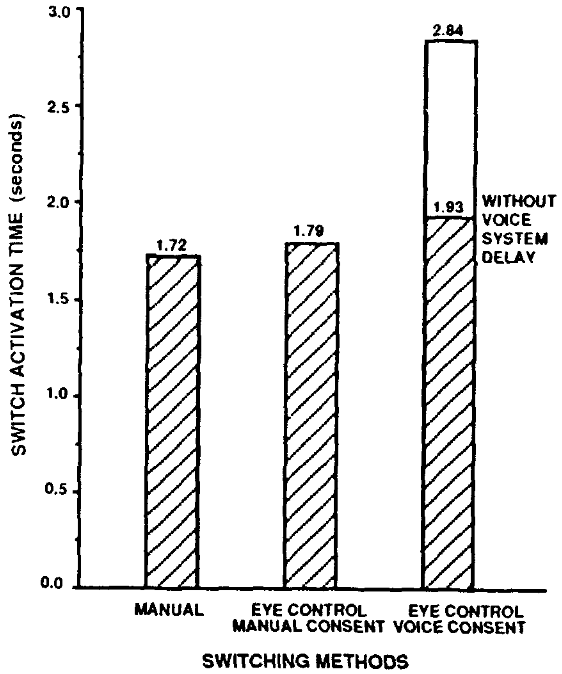


Figure 7. Mean Switch Activation Time for each Switching Method.

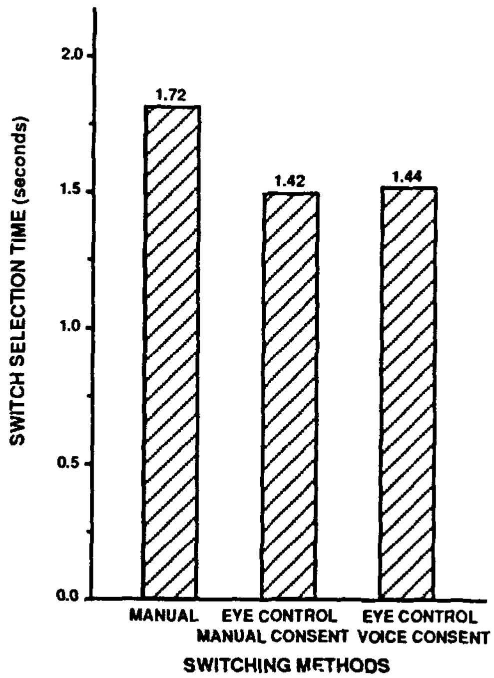


Figure 8. Mean Switch Selection Time for each Switching Method.

eye-control methods, subjects selected an average of 1.19 switches. (The number of switches selected did not significantly differ between the two eye-control methods, $F(1,5) = 0.005$, $p = 0.9473$). Thus, even though the subjects occasionally selected wrong switches prior to the correct switch before making the consent response, the mean switch selection time for the eye-control methods was less than that for the manual method.

The three switching methods differed in their impact on the tracking task, $F(2,10) = 5.34$, $p = 0.0264$ (Figure 9). RMS error for the eye control with voice consent method (0.78 inches) was found to be significantly worse than RMS error for the manual method (0.59 inches; $p < 0.05$).

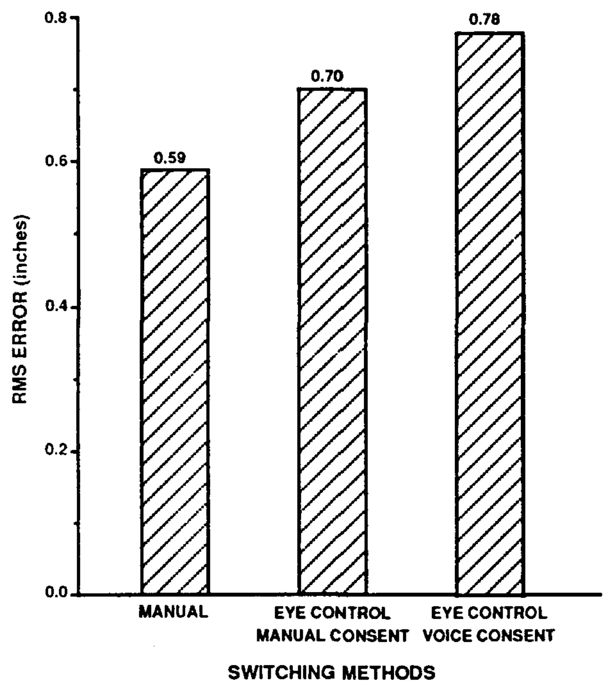


Figure 9. Mean RMS Error for each Switching Method.

Cued Switch. The switch activation time significantly differed as a function of the cued switch, $F(5,25) = 3.36$, $p = 0.0185$, Figure 10. Time to activate Switch 5 (1.95 seconds; far right switch) was significantly longer than the time to activate Switch 1 (1.66 seconds; upper left switch; see Figure 5.)

Switch selection time also differed significantly as a function of the cued switch, $F(5,25) = 3.44$, $p = 0.0167$, Figure 10. The time required to select Switch 5 (1.65 seconds; far right switch) and Switch 6 (1.59 seconds; bottom left switch) was significantly longer than the

time required to select Switch 1 (1.38 seconds; top left switch; $p < 0.05$). The number of switches selected in the two eye-control methods also significantly differed as a function of cued switch, $F(5,25) = 4.52$, $p = 0.0045$, Figure 11. More switches were selected before activating Switches 5 and 6 (1.33 and 1.26 switches, respectively) than for Switch 1 (1.03 switches).

Mean RMS tracking error did not significantly differ across the six cued switches, $F(5,25) = 1.30$, $p = 0.2939$.

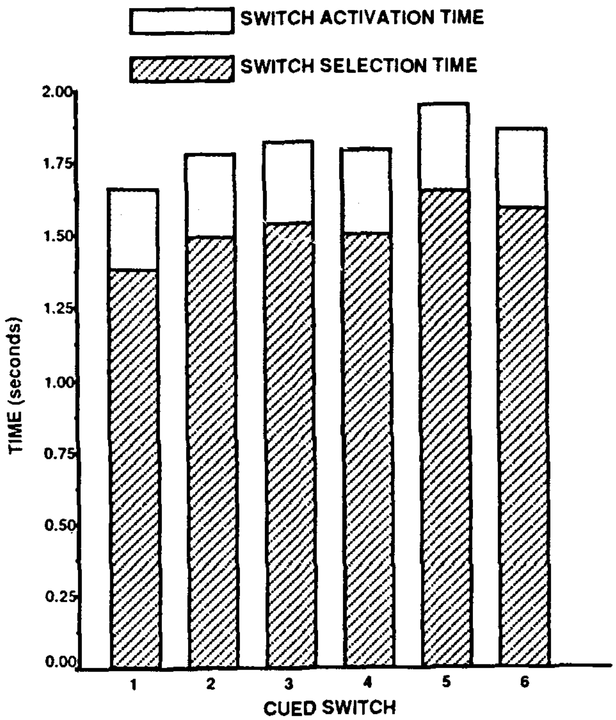


Figure 10. Mean Switch Selection Time and Activation Time for each Cued Switch.

Switching Method as a function of Cued Switch. The interaction of switching method and cued switch was not found to be significant for any of the ANOVAs reported above. The specific results for each dependent variable are as follows:

mean switch activation time - $F(10,50) = 2.48$, $p = 0.1339$;
mean switch selection time - $F(10,50) = 1.59$, $p = 0.1379$;
number of switches selected (two eye-control methods only) - $F(5,25) = 0.69$, $p = 0.6321$.

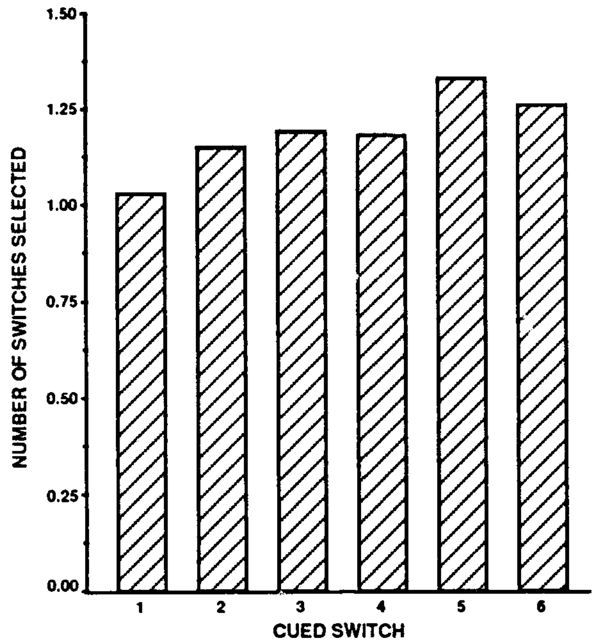


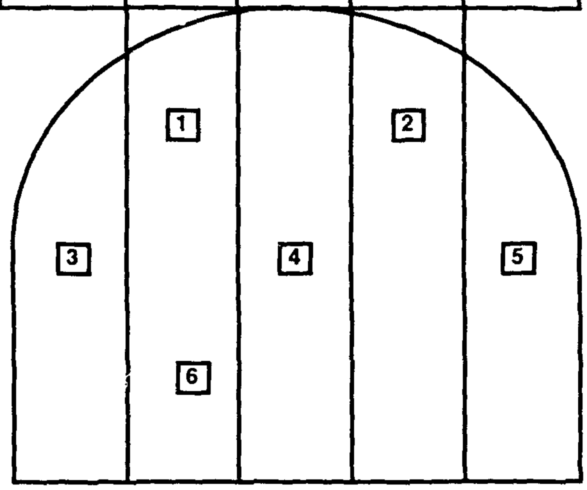
Figure 11. Mean Number of Switches Selected for Each Cued Switch.

Switch Panel Zones. In addition to analyzing performance as a function of cued switch (see above), performance was also examined as a function of several areas of the switch panel. For one analysis, the switches were regrouped into five vertical zones (see Figure 12a). Three horizontal zones were examined in another analysis (see Figure 12b). Switch selection time and activation time were averaged for each subject across trials for each switch zone. Mean switch selection and activation times for each zone are shown in Figure 12.

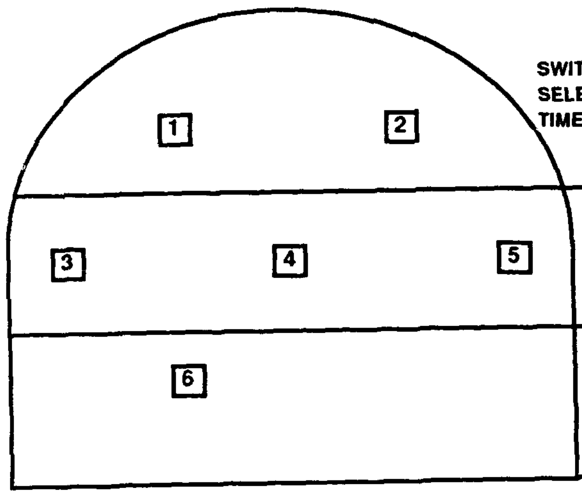
Results of the ANOVAs indicated that switch activation time and switch selection time did not differ significantly across the five vertical zones ($F(4,20) = 2.28$, $p = 0.0961$ and $F(4,20) = 2.11$, $p = 0.1178$, respectively). In separate ANOVAs, activation and selection times were also found to not significantly differ across the three horizontal zones ($F(2,10) = 3.42$, $p = 0.0736$ and $F(2,10) = 3.95$, $p = 0.0545$, respectively). The ANOVA did show that selection time differed across horizontal zones as a function of switching methods ($F(4,20) = 3.04$, $p = 0.0415$, Figure 13). Subsequent analysis showed that for the two eye-control methods, mean switch selection time was significantly less for the top row than that for the middle and bottom rows ($p < 0.05$). In addition, for the top row, mean selection time was longer for the manual method than that for the two eye-control methods ($p < 0.05$).

A. FIVE VERTICAL SWITCH PANEL ZONES

	1	2	3	4	5
SWITCH ACTIVATION TIME (seconds)	1.82	1.76	1.79	1.78	1.95
SWITCH SELECTION TIME (seconds)	1.54	1.48	1.50	1.49	1.65



B. THREE HORIZONTAL SWITCH PANEL ZONES



SWITCH SELECTION TIME (seconds)	SWITCH ACTIVATION TIME (seconds)
1.43	1.71
1.56	1.85
1.59	1.86

Figure 12. Mean Switch Selection and Activation Time for each Switch Panel Zone Examined.

<u>Tracking Performance During and Between Switching Operations</u>. In order to determine the effect of completing the switching operation on the continuous tracking task, RMS tracking error during the switching trials (i.e., from switch cue presentation to switch activation) was compared, in an ANOVA, to RMS tracking error between switching operations. The results showed that RMS tracking performance differed

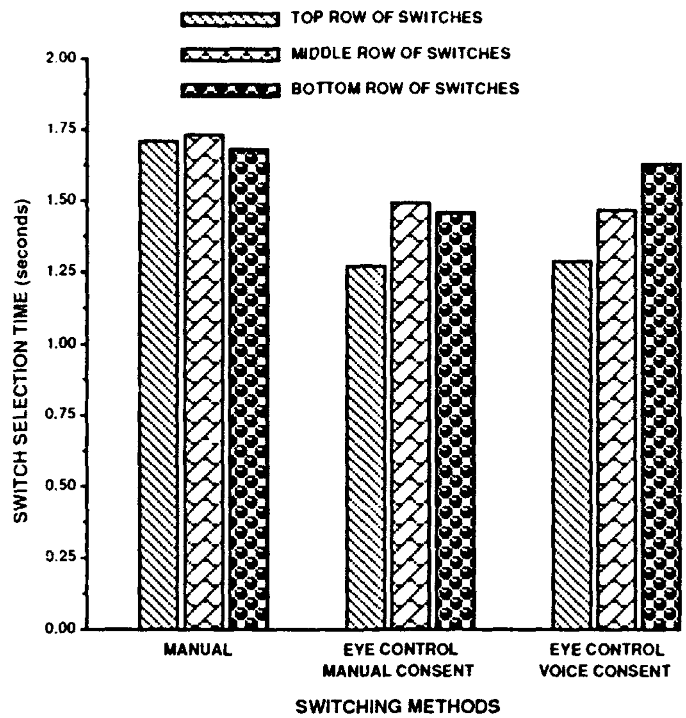


Figure 13. Mean Switch Selection Time with each Switching Method for the Three Horizontal Switch Panel Zones.

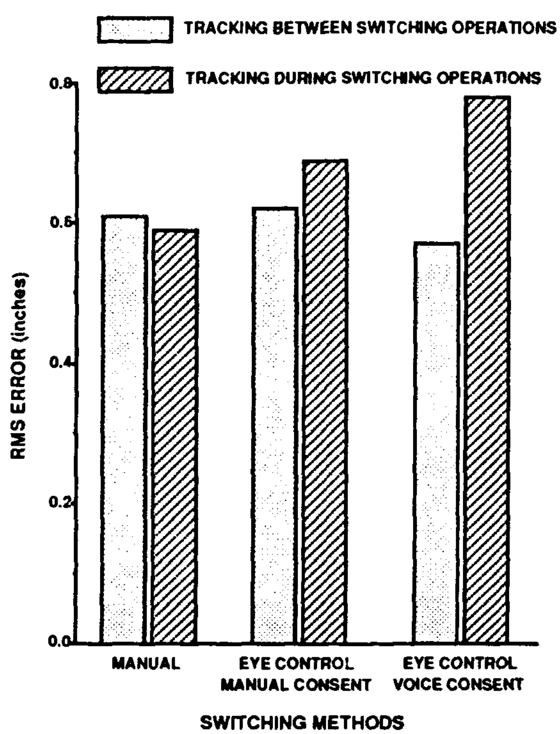


Figure 14. Mean RMS Tracking Error with each Switching Method During and Between Switch Operations.

as a function of the presence of the switching task ($F(1,5) = 22.64$, $p = 0.0051$). These results should be interpreted in light of the significant interaction of switching method and switching task presence, $F(2,10) = 16.46$, $p = 0.0007$ (see Figure 14). Subsequent analyses confirmed that tracking performance only significantly differed as a function of the presence of the switching task in the eye switching method that involved a voice consent. In this method, tracking performance was worse during the switch operations (RMS error = 0.777) compared to performance between switch operations (RMS error = 0.572; $p < 0.05$).

TRIALS WITH ERRORS IN SWITCH ACTIVATION - DUAL TASK SESSIONS

The following results pertain to trials in which the subjects activated the wrong switch when completing the switching operations while simultaneously completing the manual tracking task.

Switching Methods. The ANOVA showed that the number of errors significantly differed across switching methods, $F(2,10) = 4.97$, $p = 0.0318$. Subsequent analysis showed that there were more errors in the eye control/voice consent switching method than the other two methods ($p < 0.05$; Figure 15). None of the other measures significantly differed as a function of switching method:

mean switch activation time - $F(2,39) = 0.47$, $p = 0.6310$
mean switch selection time - $F(2,39) = 1.07$, $p = 0.3530$
number of switches selected in the two eye-control methods - $F(1,5) = 5.54$, $p = 0.0653$
RMS tracking error - $F(2,39) = 0.05$, $p = 0.9502$

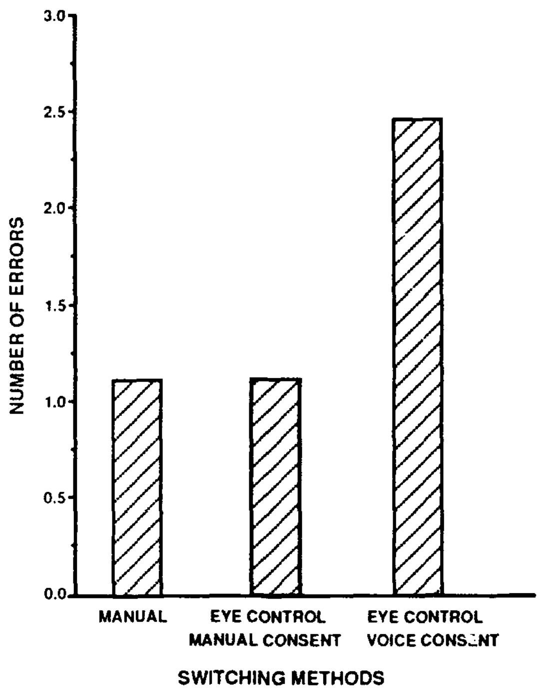


Figure 15. Mean Number of Switch Activation Errors as a Function of Switching Method.

Cued Switch. None of the analyses showed significant performance differences as a function of switch cued. Specifically, the results for each dependent variable were as follows:

mean switch activation time - $F(5,39) = 1.48$, $p = 0.2201$
mean switch selection time - $F(5,39) = 1.20$, $p = 0.3249$
number of switches selected (two eye control methods only) - $F(5,25) = 2.52$, $p = 0.0558$
RMS tracking error - $F(5,39) = 0.66$, $p = 0.6561$
number of errors - $F(5,25) = 2.35$, $p = 0.0702$

TRIALS WITH ERRORS IN NOT COMPLETING THE CONSENT RESPONSE - DUAL TASK SESSIONS

Subjects failed to make the consent response (manual button selection or verbal response) with the eye-control methods in 3.22% of the trials in the dual task sessions. The results of the analyses conducted on these trials, centering on main effects, showed no significant performance differences on any of the measures as a function of switching method or cued switch. Although the differences were not significant, it is interesting to note that the subjects failed to complete the consent response more frequently in the eye control/voice consent method than the eye control/manual consent method (2.60 versus 1.48 errors, respectively). Also, subjects selected 85.7% more switches in the eye control/voice consent method than the eye control/manual consent method. Note that the analyses were not conducted on switch activation time and switch selection time (since, without the consent response, the last selected switch can not be determined). The results for each dependent variable are shown below:

Switching Method (two eye-control methods):

number of switches selected - $F(1,5) = 2.72$, $p = 0.1602$
number of errors - $F(1,5) = 2.47$, $p = 0.1771$
tracking error - $F(1,51) = 0.90$, $p = 0.3473$

Cued Switch:

number of switches selected - $F(5,25) = 0.97$, $p = 0.4578$
number of errors - $F(5,25) = 0.73$, $p = 0.6060$
tracking error - $F(5,51) = 0.83$, $p = 0.5363$

SINGLE TASK SESSIONS

The following results pertain to the two sessions with each switching method in which subjects only completed the switching operations. The tracking task symbology was not presented and the subjects were instructed to fixate on a dot in the center of the tracking display between auditory switching cues.

The results of analysis of the error-free performance during the

two single task sessions conducted with each switching method were similar to the results obtained from examination of the sessions with the simultaneous tracking task. Switch activation time was significantly longer ($p < 0.05$) with the eye/voice consent method compared to the other two switching methods when the time data was not corrected for the voice system delay. Subtraction of the lag resulted in no performance differences between the switching methods for any of the measures (e.g., mean switch activation time: ($F(2,10) = 0.82$, $p = 0.4682$).

Also similar to dual task analyses, the analysis of error data showed a significant difference in the number of incorrectly activated switches across switching methods ($F(2,10) = 5.67$, $p = 0.0226$) and that there were significantly more errors with the eye control/voice consent method than with the manual method (4.03 versus 1.36 errors, respectively). There were no performance differences as a function of cued switch, $F(5,25) = 0.63$, $p = 0.6797$. Additionally, as was found for dual task sessions, there were no significant differences in the number of trials where the subjects failed to complete the consent response in the two eye-control methods as a function of switching method ($F(1,5) = 0.87$, $p = 0.3950$) or cued switch ($F(5,25) = 0.49$, $p = 0.7832$).

During the experiment, one single task session (switching task with no tracking) was conducted before and one session after the dual task sessions. An analysis was conducted on the error-free trials to specifically examine whether performance significantly differed between these first and last sessions. The results showed that mean switch activation time, corrected for voice system delay, did not differ between the two sessions ($F(1,5) = 1.05$, $p = 0.3524$; second session averaged 0.081 seconds less than first session). The results also showed that performance did not significantly differ between the two sessions as a function of eye condition or cued switch ($F(2,10) = 0.14$, $p = 0.8718$ and $F(5,25) = 0.07$, $p = 0.9967$, respectively). Similarly, the interaction of switching method by cued switch as a function of the pre/post sessions was also not significant ($F(10,50) = 1.42$, $p = 0.1991$).

DISCUSSION

The foregoing paragraph presented results pertaining to the lack of significant performance differences between the first and last session for the three switching methods conducted with each subject. These sessions were single task sessions in which the subjects completed only the switching operations and not the tracking task. The fact that additional experience on the switching operations between the pre and post sessions did not result in improved performance suggests that the procedures to complete the switching operations were straightforward. Moreover, the results imply that selecting the switches with eye control was intuitive and did not require special training.

In regards to accuracy, the findings illustrate how the type of consent response used with eye control can determine switching error rate. Implementation of a voice consent with eye control resulted in a very high rate of errors (close to 10% in the dual task sessions) in which either the wrong switch was activated or the subject failed to complete the consent response. It is plausible that this high error rate reflects the occasional difficulty with the voice system recognizing some of the subjects verbal responses, despite the fact that individual recognition files were generated for each subject and the vocabulary size was small (namely, one word: "go"). If the voice system did not recognize the subject's first attempt, thus requiring the subject to repeat the verbal consent, there was an increased probability of 1) an erroneous switch being selected as the subject changed visual attention to the tracking task or 2) the five-second "time-out" period expiring. In contrast, the error rate with the eye control/manual consent method was very low (2.23%) and not significantly different from the error rate found with the manual switching method. Thus, these results suggest that eye control with a manual consent results in very accurate switch activation for the experimental paradigm used in this experiment.

Not only was selecting switches with the eye intuitive and accurate (with a manual consent) in the present study, but it was faster than selecting switches with the left hand. Considering the relative movement velocity of the eye and hand and the distance the eye and hand had to travel from, respectively, the tracking display and left console, these results are not surprising. Similar results may not be found with a concurrent visual tracking task that either involves a wider field-of-view or makes more severe demands on attention. Supporting the recommendation that a variety of task paradigms needs to be evaluated, are the results from the present study pertaining to switch selection time as a function of switch cued. The results indicated that it took less time, with eye control, to select the left and uppermost switch on the control panel, than the switches on the far right, bottom row locations. These results may reflect the smaller distance through which the eye was required to travel from the tracking monitor to the top row switch, compared to the switches towards the bottom of the panel. It could also be that the results suggest that execution of eye movements in implementing the eye control involved left to right, top to bottom movements, similar to what is used when reading a page. Another

possibility is that the performance difference across control panel areas is an artifact of the eye tracking system; perhaps the system which monitors position of the right eye more accurately tracks movements in the left forward field, compared to the right field. Further research would clarify these results. Nevertheless, for applications similar to the paradigm used in the present experiment, these results demonstrate that eye tracking technology can effectively enable rapid selection of switches via direction of the gaze.

However, regardless of the speed in selecting switches, the time and accuracy of making the consent response required in implementing an eye control interface need to be considered. The longer switching time with the eye control/voice consent method in the present study illustrates the importance of examining the total switching time, from the beginning of the switching task to the closing of the consent switch, when comparing control mechanisms. The delay introduced by the voice recognition equipment components and by the duration and acceptance of the utterance resulted in a corresponding inflation in overall switching time. Unless significant advances are made in voice recognition technology, a voice consent will probably take longer to complete than a manual consent. However, for less time-critical crew station tasks or flight segments in which the manual channel is heavily loaded, a voice consent may be appropriate.

Looking at overall switching time recorded when a manual consent was used with eye control, the results indicated that eye control is a practical method for activating switches mounted in the central field-of-view. The mean switching time difference of less than a tenth of a second between the eye with manual consent method and the manual method indicates that eye-controlled switching is a feasible and practical alternative to manual switching.

Examination of these data from the present experiment also indicated that switching performance was not significantly impacted by the presence of the tracking task. Although one would expect switching performance to be severely impaired by the addition of a simultaneous task, overall switch activation time in the present experiment was 0.141 seconds faster during dual task sessions, compared to single task sessions. These results could reflect a strategy to complete the switching task as quickly as possible in order to resume the tracking task. Plus, the presence of the tracking task could have had an attention arousal effect. Comparison of the switching data from single task sessions with data from the dual task sessions showed similar trends in the results in regards to performance with each switching method and cued switch.

For the most part, tracking performance was also not impacted by the presence of the switching task. This was determined by looking at the tracking performance during and between switching operations in the dual task sessions. The only switching method in which tracking performance was poorer during switching operations was the eye control with voice consent method. This is thought to be due to the subjects' occasional difficulty in getting the voice system to accept the verbal

response, along with the corresponding increase in overall switching time. The subjects were apparently distracted by their conscious attempts to vary the pitch/volume of their vocal response and elicit correct recognition. Improvements in voice recognition accuracy might mitigate these tracking performance differences.

Even though the above findings suggest that selection of switches in a central location via eye control is practical with a concurrent manual tracking task, additional research is needed to determine whether other implementations of eye control (e.g., slewing a sensor) are feasible with a variety of task-loaded conditions. Common concurrent visual tasks in the cockpit include visual feedback of a continuous tracking task, searching for a target, and visual monitoring of displays. Each of these tasks places unique demands on visual attention. Follow-on research is necessary to clarify these findings, as well as indicate whether eye-controlled switching is feasible with a variety of task-loaded conditions.

Next, optimization of the mission task/control interface assignment needs to be accomplished. Eye control is a natural interface for those tasks in which the pilot is already involved in aiming the eyes, for instance when acquiring a target within visual range. However, there are also some piloting tasks in which conventional manual control is more appropriate (e.g., numeric entry on a keypad during mission planning). Also, it is plausible that there are control actions which pilots would prefer to be dedicated to a manually operated device (e.g., master arms switch). It is also possible that procedures could be implemented by which pilots have the option of specifying the control action they desire. This could be especially beneficial when the pilot is under acceleration forces when it is difficult, if not impossible, to move the arm and hand to make anything more than a fine control movement. Eye control is a promising candidate interface for control operations under acceleration, because, whatever the level of acceleration, vision is not disturbed for at least 3-5 seconds after the beginning of the exposure (due to a small store of oxygen dissolved in the extravascular fluid of the retina). Additionally, at moderate levels of acceleration, the intensity of the visual symptoms often decreases 8-12 seconds after the onset of the acceleration due to compensatory cardiovascular reflexes which restores the flow of blood to the retina (Sharp, 1978). Moreover, there are several acceleration protection methods (anti-G suits and straining methods) which increase the blood flow to the eyes and the brain and make it more likely that the oculomotor system will remain an effective control interface.

Similarly, future efforts should also evaluate other applications of eye control in crew stations design. In addition to switch selection, eye control may be a natural interface for designating or updating symbology or data on a display. For tasks in which the pilot's attention is directed out of the cockpit, eye control would enable the control portion of these tasks to be completed with vision out of the cockpit and the hands on the flight controls. Continued investigation will help determine which tasks and what methods of implementation (e.g., modality of consent, etc.) are most appropriate for eye control.

The advisability of having multiple control mechanisms in effect should also be investigated. This could allow the pilot to choose which mechanism to exercise, or enable algorithms residing in onboard processors to choose the control mechanism(s) appropriate for the current workload environment or pilot state.

The evaluation of eye-controlled switching reported herein is the first, in a series of investigations to compare performance with eye control to other interfaces in a variety of task environments. The results from these studies, together with efforts underway in several industries to improve sensing of eye and head position and rotation, suggest that integration of eye/head position monitoring devices will make control of crew station tasks by the pilot's eye line-of-sight practical.

APPENDIX A

SWITCHING STUDY - SUBJECT INSTRUCTIONS

INTRODUCTION

Thank-you for serving as a subject in the Helmet-Mounted Oculometer Facility. As explained to you during the linearization session, the unique feature of this system is its ability to accurately measure your helmet and eye position. From these data, we can determine your eye line-of-sight (LOS) or where your eye is looking in the cockpit. The purpose of this experiment is to examine how eye LOS can be used to select switches. The successful application of such techniques in the cockpit could reduce pilot workload by permitting the pilot to control functions without removing the hands from the stick and throttle.

During this experiment, we will be looking at three methods of selecting switches. In two of the methods you will select the switches by looking at them, and then give a consent response either by pressing a switch or saying the word "GO". In a third method you will select switches manually with your left hand. We will evaluate the speed and accuracy of your switching operations, both when switching is your only task, and also when you have a concurrent tracking task. We will also be looking at your responses and comments to questionnaires that we will periodically administer. Through your efforts, we will be able to determine whether eye LOS is a candidate control interface for future cockpits.

SET UP

Now we'd like to get you set up in the cockpit. As you climb in, we ask that you avoid stepping on the switch on the left console. Next, we'll adjust your seat before fitting the helmet on you. There are several things you need to know about the care of the helmet and visor:

1. Please don't touch the visor. The visor must be kept very clean; and, as a precautionary measure, we would like you to wear cotton gloves throughout the entire session. You should still exercise extreme caution in avoiding contact with the visor, but in the event you do, the gloves serve as an aid in reducing the amount of skin oil that gets on the visor.

2. Once we place the helmet on your head with the necessary helmet pads inserted, fasten the chin-strap.

3. Once the chin-strap is fastened, inflate the ear bladders until the helmet feels snug on your head.

4. We will raise and lower the helmet visor for you, and attach the helmet cables to the seat for greater comfort.

5. In the event you need to move or reposition the helmet, please advise us so we may assist you.

6. Remember, be very careful not to bump the visor against any surface, or touch the visor, especially the reflective patch over your right eye.

7. If an emergency should occur and you need to get out of the helmet without assistance, perform the following steps in order:

a) Raise the visor by pulling the visor clip outward. The visor clip is located on the upper left side of the helmet.

b) Let the air out of the air bladder by turning the valve near the bulb.

c) Unfasten the chin-strap.

d) Release the helmet cables on the upper right of the seat by pulling the velcro strap.

e) Carefully take off the helmet and place it on the seat without bumping the visor.

f) Exit through one of the two doors in the lab.

8. There is a light pen on the canopy in the event of a power outage.

9. We ask that during the runs you keep your right hand on the force stick and your left hand on the left console switch cover.

TASKS (Only paragraphs describing conditions in the next scheduled test session are to be read.)

You will have two tasks in this experiment, and we want you to give equal consideration to both tasks. Your performance on both tasks will be recorded and analyzed. In order to encourage high performance, we're going to employ a financial incentive system whereby you get a bonus of 50 cents when performance on either task improves by more than 1 standard deviation from its previous day's level. The bonus will increase to $1.00 if both tasks improve, and will be reduced to 25 cents if neither task improves by more than 1 standard deviation. If either task deteriorates from the previous day, no bonus will be awarded. Any and all bonuses earned will be awarded upon completion of the experiment.

1. UPPER MONITOR TASK

No Tracking: During this session, one of your tasks is to fixate on the dot on the upper monitor.

Tracking: During this session, one of your tasks will be a manual pursuit tracking task instead of fixating on a dot. The symbology presented on the upper monitor for the tracking task will be a dot and a cross hair. By applying force on the joystick, your task is to put the dot on top of the continually moving cross hair. Continue tracking until the dot disappears from the monitor. Your performance will be measured in terms of the average distance of the dot from the cross hair during a run.

2. SWITCHING TASK

While you are (fixating on the dot) (tracking), you will be required to select switches on the center panel. Both speed and accuracy will be examined. You will be prompted as to which switch to select on the center panel by the speech synthesizer (e.g., "one", "two",..."six"). These prompts will be received through the headset implanted within the helmet.

Eye Control: Upon receiving the prompt, your task is to direct your eye to the designated switch in order to illuminate it. Once the switch lights, give a consent by (depressing the switch on the top left corner of the joystick) (saying the word "GO". If the computer recognizes your command, it will echo the word "GO", otherwise a tone will be heard and you must repeat the word "GO"). Once the consent is accepted, the switch light will go out. Resume (fixation on the dot) (the tracking task) either after the switch is lit or after the consent is given, whichever feels most comfortable for you.

You will have 5 seconds to complete the switch operation. If the switch doesn't light, you may decide to resume the task on the upper monitor before the 5 seconds are up to await the next prompt.

Manual: Upon receiving the prompt, your task is to depress the switch with your left hand and then return your left hand to rest on the left console switch cover. Resume the task on the upper monitor (either fixation on the dot or the tracking task), either after the switch is pressed, or after your left hand is returned to the left console, whichever feels most comfortable for you.

3. Follow these procedures throughout the entire run for each verbal prompt.

BORESIGHT PROCEDURE

1. Before each run, it is necessary to "tune" the system to the particular characteristics of your eye and the position of the helmet on your head. This procedure, which we call "boresighting", includes staring at dots on the upper monitor and six of the seven switches on the center panel. Data is collected for each point by depressing the trigger switch on the joystick.

2. To begin the boresight procedure, depress the center switch (4) on the front switch panel. The verbal command "START BORESIGHT" will be heard through the headset and a dot will appear in the center of the top monitor. This is the first boresight point. Once you feel you have a good, steady fixation on this dot, give the trigger switch on the force stick a single press to begin the data collection process. Again, it is very important that you maintain a steady fixation on this point once the trigger switch has been depressed and until the point disappears. After approximately six seconds, the dot will disappear and the next boresight point will appear in the upper left-hand corner of the monitor. This is the second boresight point. At any time before

depressing the trigger switch you may momentarily rest your eyes before continuing. Once ready, again, look at and fixate on the dot, depress the trigger switch to begin data collection, and maintain a steady eye fixation until the dot disappears and the next boresight point is presented. Follow these steps for the entire boresight procedure. There are six boresight points on the upper monitor (center, top left corner, top right corner, bottom left corner, bottom center, and bottom right corner).

3. Following the sixth boresight point on the upper monitor, you are to boresight the center panel of switches. The procedures for boresighting a switch is the same as for a dot. You will be boresighting six of the seven switches.

4. If you fail to boresight on any of these 12 points, please let us know.

5. Following the boresight procedure, we will look at a plot of your boresight fixations. If the boresight data looks good, we will momentarily start the first run; otherwise, we will ask you to repeat the boresight procedure.

6. Between runs, the speech synthesizer will issue the verbal command "CONFIRM BORESIGHT". At this time, you can test your boresight by looking at, and lighting each switch, in turn. If you have difficulties, you will be required to repeat the boresight procedure.

START-UP

1. First, I will close the curtain. Your eyes will be dark-adapted for about 5 minutes. You may use this time to rest your eyes, but we ask that you don't push any switches.

2. We will be in communication through the intercom during the entire session. Feel free to ask questions between runs.

3. After the dark adaptation period, I'll inform you that I'm turning on the light source (you'll see the red filament image reflect off the visor). I may have to adjust the helmet some to get a better image of your eye. I will also tell you when to begin the boresight procedure by depressing the center switch (4). Please let me know between runs if you need to have your helmet adjusted, or if you have any questions.

We will run four 5-minute runs, give you a short break in the cockpit and then another four 5-minute runs. It may take several weeks, running approximately every other day, to collect the data that we need.

4. Any questions?

APPENDIX B

SUBJECT QUESTIONNAIRES

Immediately after the last run with each switching condition, each subject was given a questionnaire concerned with that switching method. The subjects' responses to these questions appear first in the appendix, followed by their responses to the final debriefing questionnaire. This final questionnaire was administered following the completion of all the data runs and was designed to elicit subjective evaluation of the three switching methods. (Editorial comments are contained within parentheses). Nonparametric Kolmogorov-Smirnov tests of significance were conducted on data obtained from the questionnaires. Results are reported where the probability associated with the observed value of the maximum deviation is smaller than $p = 0.05$.

HMOF Switching Study
Interim Questionnaire

1. The steps required to select and activate switches were:

	Eye/Voice	Eye/Manual	Manual*
Very Easy to Perform	3	3	5
Moderately Easy to Perform	2	2	1
No Opinion	0	1	0
Moderately Difficult to Perform	1	0	0
Very Difficult to Perform	0	0	0

*Manual: $\underline{D}(6) = 0.633$, $\underline{p} < 0.01$

Comments/Improvements: (None)

2. Rate the acceptability of this method in terms of speed in completing the switch operations:

	Eye/Voice	Eye/Manual	Manual*
Unacceptable	0	0	0
Bad	0	0	0
Satisfactory	2	2	0
Good	3	2	5
Optimum	1	2	1

*Manual: $\underline{D}(6) = 0.600$, $\underline{p} < 0.05$

Comments/Improvements:

Eye/Voice

- (Good) The voice recognition system seemed to slow down things.

Eye/Manual

- (Satisfactory) Had trouble at times getting switches to light.

- (Satisfactory) Depended upon the run (boresight).

Manual

- (Good) Sometimes I felt like I had to really reach to activate a switch, which could make it a slower process of pushing in the switches.

- (Good) It didn't seem quite as fast as switching with my eyes.

3. Rate the acceptability of this method in terms of accuracy in completing the switch operations:

	Eye/Voice	Eye/Manual	Manual
Unacceptable	0	0	0
Bad	0	0	0
Satisfactory	4	2	1
Good	2	3	2
Optimum	0	1	3

Comments/Improvements:

Eye/Voice

- (Satisfactory) At times the switch would change when I said Go.

- (Satisfactory) Computer didn't recognize my voice some of the time.

- (Satisfactory) I sometimes had problems with unintentionally lighting the wrong light after I had gotten the right light on.

Eye/Manual

- (Satisfactory) Depended upon the run.

- (Satisfactory) I feel a lot of the time, I was not the cause for the switches not lighting up. Maybe some mechanical cause?

- (Good) The wrong lights (switches) would light up sometimes, especially (switch) #2 when looking at (switch) #5.

Manual

- (Good) The large switches and large spacing between them allows for a high degree of accuracy.

4. Were you able to perform the tracking task while you were completing the switch operations?

	Eye/Voice	Eye/Manual	Manual
Yes	5	4	6
No	1	2	0

Comments/Improvements:

Eye-Voice

- (No) Between switch operations yes, (but) during switch operations, no.

Eye/Manual

- (No) This seemed to be the only drawback to this method of switch selection.

Manual

- (Yes) Didn't need to look at the switches to light (select) them.

- (Yes) You can get a general idea of where the switches are, so a lot of attention can be directed towards the tracking.

5. How did the selection of switches affect completion of the tracking task?

Switch selection ...

	Eye/Voice	Eye/Manual	Manual
Aided Greatly	0	0	2
Did Not Interfere or Aid	0	0	0
Interfered Slightly	6	4	3
Interfered Greatly	0	2	1

... with the tracking task.

Comments/Improvements:

Eye/Voice

- (Interfered Slightly) Sometimes it interfered greatly when I couldn't get the light to come on.

Eye/Manual

- (Interfered Slightly) It interfered greatly when I didn't get the light on right away.

- (Interfered Slightly) When I had to turn my attention to the switching, tracking was ignored.

- (Interfered Greatly) I could not track at all when I was lighting the switch. Also, when you pushed the button (on the joystick) in, the dot jumped requiring you to readjust (the dot) over the cross (hair).

- (Interfered Greatly) Put the (consent) button to be pushed elsewhere where it could be pushed with the left hand.

Manual

- (Interfered Slightly) It might have aided slightly by keeping me from becoming too bored with the tracking task.

6. Do you have any other comments you would like to make concerning this method of switching?

Eye/Voice

- Helmet is heavy. I still had a glare on the visor. I liked this condition the best (compared to Manual and Eye/Manual).

Eye/Manual

- This seemed to be the fastest and most accurate of the three methods. It did though, interfere greatly with the tracking task, perhaps because the location of the button caused me to move the stick when I pushed the button.

- Not very reliable. Helmet is heavy. Had problems with the glare coming off the helmet.

Manual

- It was the easiest of them all.

- Helmet was somewhat uncomfortable. I also had a strong glare on the helmet (visor) which interfered with my tracking.

- It seemed to be more accurate but a little slower than switching with my eye (eye-voice).

HMOF Switching Study
Final Questionnaire

1. Compare the overall usability of the three switching methods for the sessions in which there was no tracking and switch selection was your only task.

	Worse Than	Slightly Worse Than	Equal To	Slightly Better Than	Better Than	
Manual	2	1	0	1	2	Eye/Manual
Manual	0	2	1	0	3	Eye/Voice
Eye/Manual	0	0	2	2	2	Eye/Voice

Comments/Improvements:

- When there was no tracking, the task was easiest.

- Sometimes, after saying go, another light would light up.

NOTE: The remaining questions address switch selection while also completing the tracking task.

2. Compare the overall usability of the three switching methods for the sessions in which you had to complete the tracking task in addition to selecting switches.

	Worse Than	Slightly Worse Than	Equal To	Slightly Better Than	Better Than	
Manual	0	3	0	1	2	Eye/Manual
Manual	1	0	2	1	2	Eye/Voice
Eye/Manual	1	0	2	3	0	Eye/Voice

Comments/Improvements: (None)

3. Rate the acceptability of each method in terms of <u>speed</u> in completing the switch operations.

	Worse Than	Slightly Worse Than	Equal To	Slightly Better Than	Better Than	
Manual	1	2	1	1	1	Eye/Manual
Manual	1	1	1	2	1	Eye/Voice
Eye/Manual	0	1	1	3	1	Eye/Voice

Comments/Improvements:

- Eye/Manual seemed to be the fastest way to do the switching.

4. Rate the acceptability of each method in terms of <u>accuracy</u> in completing the switch operations.

	Worse Than	Slightly Worse Than	Equal To	Slightly Better Than	Better Than	
Manual	1	0	1	1	3	Eye/Manual
Manual	0	1	0	2	3	Eye/Voice
Eye/Manual	0	0	3	1	2	Eye/Voice

Comments/Improvements: (None)

5. Rate the acceptability of each switching method in terms of interference with the concurrent tracking task.

	Worse Than	Slightly Worse Than	Equal To	Slightly Better Than	Better Than	
Manual	0	1	0	2	3	Eye/Manual
Manual	0	1	0	3	2	Eye/Voice
Eye/Manual	0	1	4	1	0	Eye/Voice

Comments/Improvements:

- On Eye/Manual, give the manual part to the left hand.

- In the manual stage I didn't have to look at the switches. I could track without interference.

- (Manual) The switching method was somewhat more difficult when I was tracking with one hand and switching with the other hand.

6. Rate the usefulness of having the switch light come on when the computer detected that a switch had been designated for:

Manual Method

Switch light was:

0 Very Distracting - 0
0 Somewhat Distracting - 0
0 Not Noticeable/No Opinion - 3
0 Somewhat Helpful - 1
0 Very Helpful - 2

Eye/Manual and Eye/Voice Methods*

Switch light was:

0 Very Distracting - 0
0 Somewhat Distracting - 0
0 Not Noticeable/No Opinion - 1
0 Somewhat Helpful - 0
0 Very Helpful - 5

*$D(6) = 0.633$, $p < 0.01$

Comments/Improvements:

Manual

- (Not Noticeable/No Opinion) On the manual light, I never knew if it came on or not.

- (Not Noticeable/No Opinion; One subject circled Not Noticeable).

- In the Manual condition, the light could stay on for a while, i.e., 0.5 or 1 sec. This would greatly improve its usefulness.

Eye/Manual and Eye/Voice Methods

- (Very Helpful) The eye condition could not have been done without the light.

7. Rate the usefulness of hearing the word "GO" after the computer recognized your verbal consent in the Eye/Voice Method.

0 Very Distracting - 1
0 Somewhat Distracting - 0
0 Not Noticeable/No Opinion - 1
0 Somewhat Helpful - 2
0 Very Helpful - 2

Comments/Improvements:

- (Very Distracting) Did not like that feature.

- (Somewhat Helpful) After so many runs the voice computer was somewhat distracting. It also seemed that some of the time the voice was quite loud.

8. How did the red filament affect your ability to select switches while completing the tracking task?

The filament was:

- 0 Very Distracting - 0
- 0 Somewhat Distracting - 3
- 0 Not Noticeable/No Opinion - 1
- 0 Somewhat Helpful - 2
- 0 Very Helpful - 0

Is your response true for all switch methods? 0 yes, 0 no. If no, specify which method(s) and explain.

Yes	No
4	2

Comments/Improvements:

- (Somewhat Distracting; Yes - true for all three switch methods) The filament was distracting in all the three switch methods. The light seemed to hurt my eyes sometimes.

- (Somewhat Distracting; Yes) The red filament put a glare on the visor which sometimes interfered with my tracking.

- (Somewhat Helpful; No) It didn't interfere and really wasn't noticeable in the manual mode.

- (Somewhat Helpful; No) The red filament was helpful for the eye conditions, manual and voice, in keeping my head steady. For the manual condition the filament didn't make any difference.

- (Somewhat Helpful; No) For the Eye/Manual and Eye/Voice methods the red light helped me to keep my head in the same position. I would do the boresight with the red light just below (switch) 4, then throughout the session, I could tell if my head was in the same position. For manual method, head position wasn't so critical, so the red light didn't make any difference.

9. Did any part of the visor affect your ability to complete the tasks? 0 yes, 0 no. If so, what part of the visor and how did it affect task performance with each switch method?

Yes	No
1	5

Comments/Improvements:

- The red filament put a glare on the visor which sometimes interfered with my tracking. Visor itself was OK.

10. Rate how comfortable you found the helmet and its attachments. The helmet was:

0 Very Uncomfortable - 2
0 Slightly Uncomfortable - 4
0 Not Noticeable/No Opinion - 0
0 Slightly Comfortable - 0
0 Very Comfortable - 0

$\underline{D}(6) = 0.600$, $\underline{p} < 0.05$

Comments/Improvements:

- (Slightly Uncomfortable) It had certain "hot spots" that tended to become irritating by the last run.

- (Slightly Uncomfortable) Usually during runs 5-8 the helmet got heavy and the top of my head ached.

- (Slightly Uncomfortable) The helmet seemed to get very heavy near the end of a session. My head started to feel really smashed at the end of the session also.

- (Slightly Uncomfortable) It wasn't bad once the nape pad was left out. Did get uncomfortable after awhile.

- (Slightly Uncomfortable) More so at times - usually during the 2nd session (Runs 5-8), the helmet got heavy on my head, and the top of my head started aching. I don't know if more pads would have helped or not.

- (Very Uncomfortable) The attachments did not bother me. The helmet is way too heavy.

- (Very Uncomfortable) At the end of a lengthy session my head always hurt. I don't easily get headaches.

11. Did you experience any eye strain, etc. from the experiment? 0 yes, 0 no. If yes, please describe.

Yes	No
3	3

Comments/Improvements:

- (Yes) My eyes dried out and began to hurt during some of the experiments.

- (Yes) I had just a little itching after I ran - maybe due to a dry eye.

- (Yes) About 50% of the time, my eyes would be tired after a session. Not too tired, just a little tired.

- (No) But I always had trouble keeping my eyes focused if I was tired, or my eyes were tired. But I had no real eye strain from the experiment.

12. Do you have any other comments you would like to make concerning this experiment (e.g., briefing, tracking task, boresight steps, or procedures)? Any feedback that you provide would be very helpful.

Comments/Improvements:

- The experiment is very interesting but maybe if you cut down on the amount of time a subject sits in the cockpit, the less uncomfortable it might be! Its just a suggestion!

- Boresighting was easy and really isn't any trouble to repeat.

- Shorter sessions would be better.

- I enjoyed running this experiment. I would consider making the experiment a little shorter - perhaps 6 runs in a row with no break as opposed to 8 runs with a break.

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